Appendix A

QUAL2E Model Calibration / Verification

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Introduction

The purpose of this document is to provide information on how the QUAL2E model for the Upper Contoocook River TMDL was calibrated and verified. Once calibrated and verified, the model can then be used to run other scenarios (i.e., predictive runs) to determine compliance with water quality standards.

QUAL2E Water Quality Model - Overview

Mathematical modeling allows one to predict and evaluate the effects of changes in the environment (i.e, stream temperature, flow, pollutant loadings etc.) on stream water quality. For this study, the enhanced stream water quality model, QUAL2Ev5, was used. QUAL2Ev5 is a one dimensional stream water quality model that can simulate the major reactions of nutrient cycles, algal production (phytoplankton and periphyton), benthic (i.e., sediment) and carbonaceous oxygen demand, atmospheric reaeration and their effects on the dissolved oxygen balance. The model is applicable to branched stream networks that are well mixed and can simulate up to 17 water quality constituents. It assumes the major transport mechanisms, advection and dispersion, are significant only along the main direction of flow (longitudinal axis of the stream) and allows for multiple discharges, withdrawals, tributary flows, and incremental inflow and outflow. The use of QUAL2E as a water quality planning tool is well documented (Brown, 2003).

QUAL2Ev5 can operate in either steady state or diurnal mode. In the steady state mode the model can be used to study the impacts of wasteloads, their magnitude, quality and location on instream water quality as well as the impacts of non point source waste loads. In the diurnal mode the user can study the effects of variations in climatological data, and algal growth and respiration on water quality, primarily dissolved oxygen. A schematic of the processes simulated by QUAL2E is presented in Figure 1.

Figure 1: Major Constituent Interactions in QUAL2E

QUAL2E – Version 5.0
Model Documentation

Chapter 4 Constituent Reactions

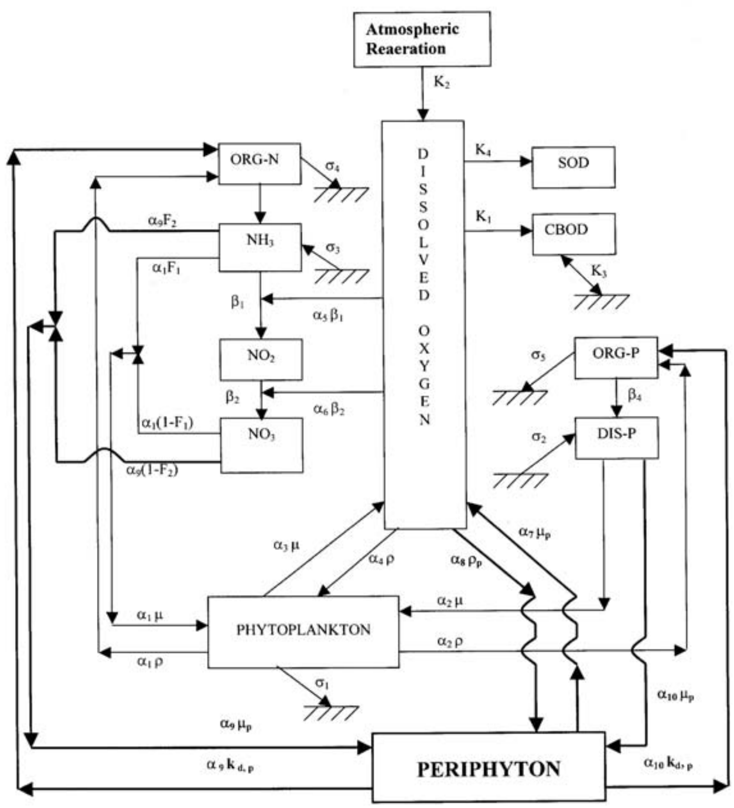


Figure 4.1 Major Constituent Interactions in QUAL2E
(to be updated, redrawn)

4-2

Study Area

As shown in Figure 2, the study area that was modeled includes approximately 9.5 miles of the Contoocook River and extends from the outlet at Cheshire Pond in Jaffrey to just downstream of the North Village dam in Peterborough. The watershed includes approximately 126.9 square miles of watershed area and begins at an elevation of 965 feet and ends at an elevation of 694 feet. Land uses in the watershed are shown on Figure 3 and are from the New Hampshire Land Cover Assessment which categorizes land cover and land use into 23 classes, based largely on the classification of Landsat Thematic Mapper (TM) imagery [2] taken between 1990 and 2001.

[2] New Hampshire GRANIT. 2001. NH Land Cover Assessment. New Hampshire GRANIT, Durham, NH."

Most of the watershed is relatively undeveloped with less than 15 percent classified as urban or agriculture. Most urbanized areas are located in relatively close proximity to the Contoocook River mainstem. Table 1 shows the percentage of each land use in the watershed.

The river in the focus area flows predominantly from south to north, is characterized by a well defined channel comprised of pools and riffles, 3 impoundments behind dams and 4 significant tributaries (Town Farm Brook, Gridley Brook, Meadow Brook and Nubanusit Brook). Within 3 miles upstream of the Cheshire Dam, there are 3 more dams on the mainstem. A schematic of the Upper Contoocook River showing the dams, tributaries, point sources, sampling stations and river reaches used in the QUAL2E model, is provided in Figure 4. A profile of the river is provided in Appendix 1-A.

Figure 2: Major Features and Sampling Location Map

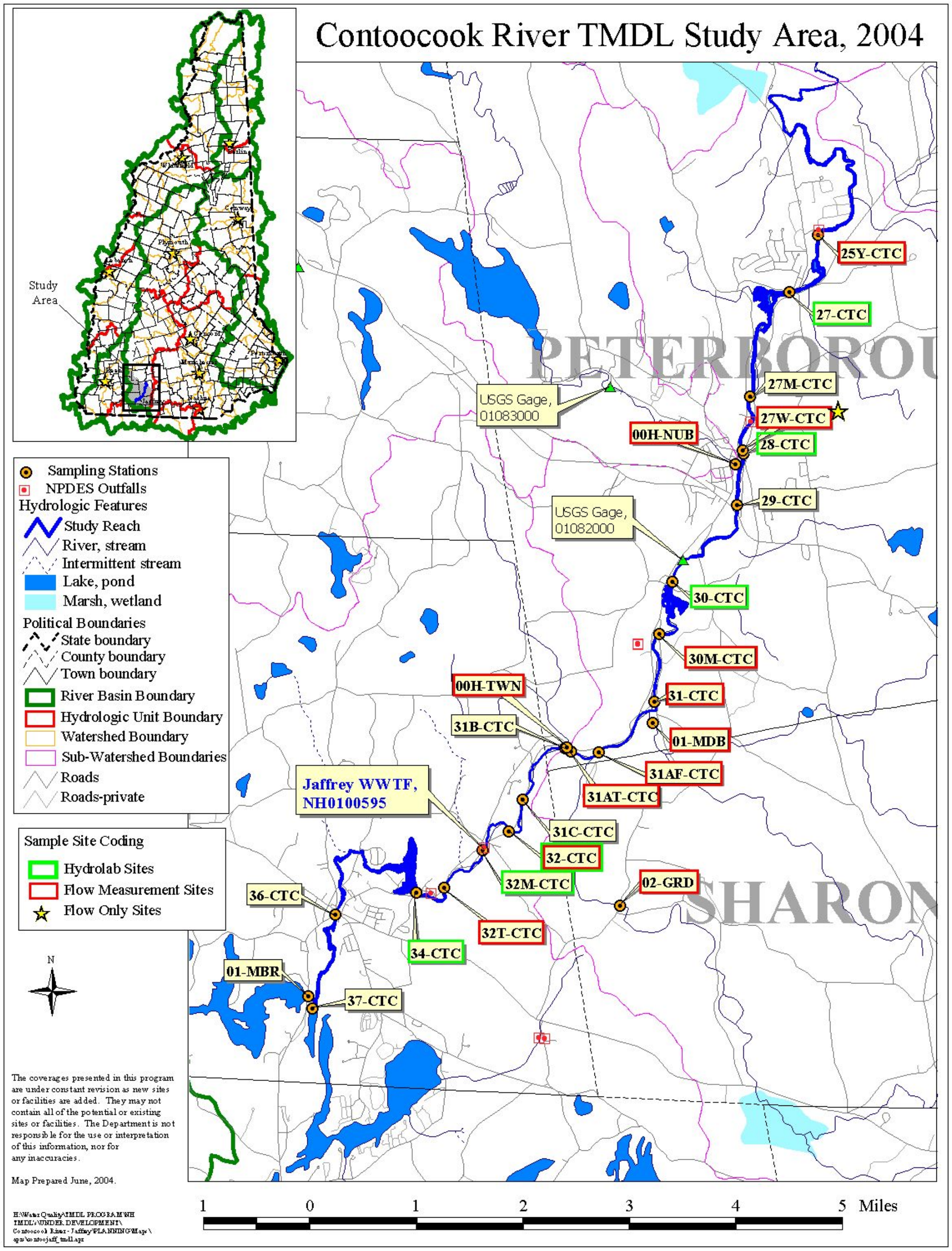
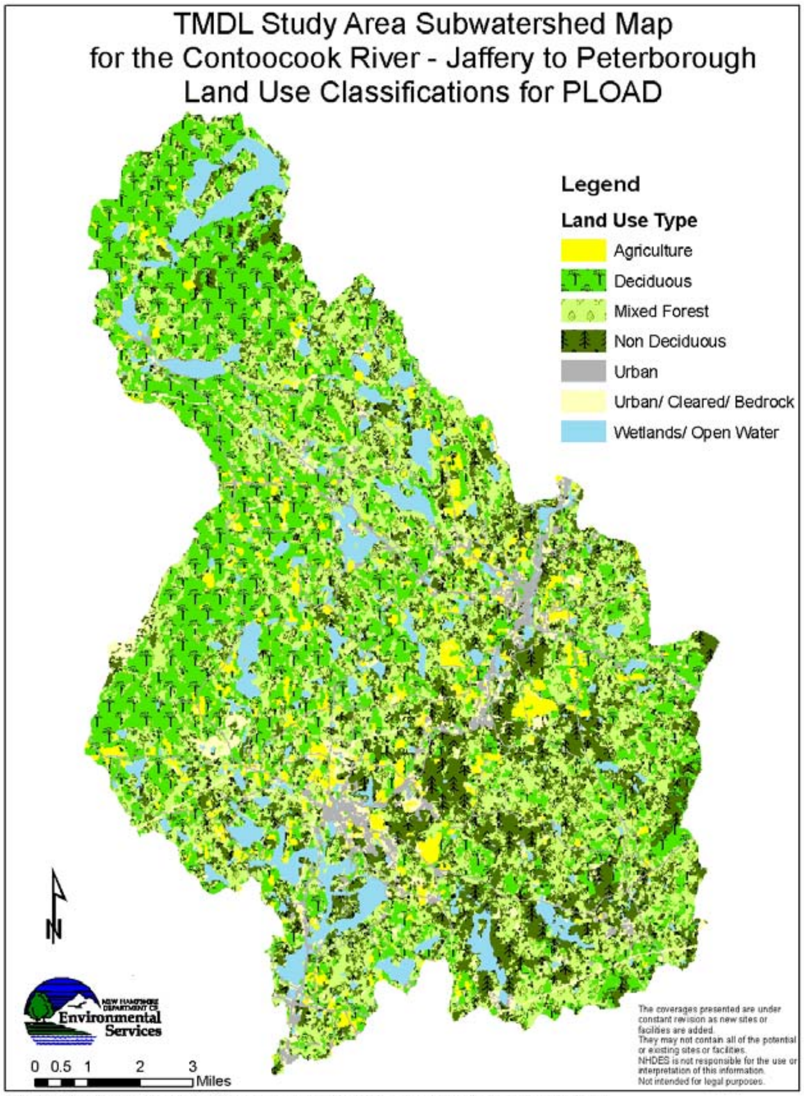


Figure 3: Land Use Map

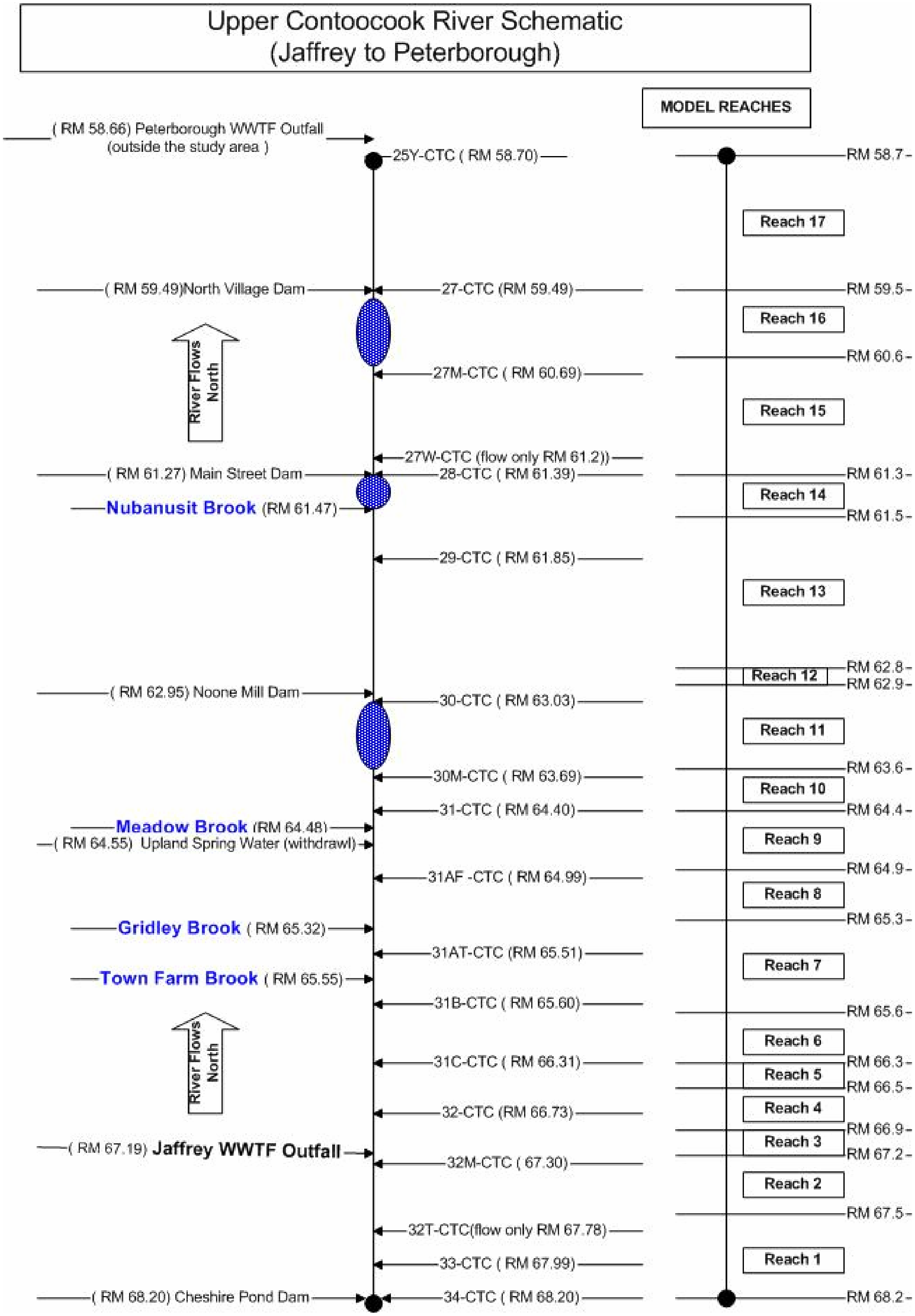


Map Document: (E:\projects\biederman\Pload\Contoocook\TMDL_CTC_Jaffery_LU.mxd) 11/9/2005 -- 9:31:28 AM

Table 1: Land Uses in the Study Area

DECRIPTION OF LAND USE TYPE	Square Miles	Percent of Total
Agriculture	5.9	4.7%
Deciduous	36.7	28.9%
Mixed Forest	38.2	30.1%
Non Deciduous	23.8	18.8%
Urban	6.8	5.4%
Urban/ Cleared/Bedrock	4.3	3.4%
Wetlands/ Open Water	11.1	8.7%
Total	**126.9**	**100.0%**

Figure 4: Schematic of the Upper Contoocook River



Note: RM = River Mile

Summary of Data Used to Calibrate/Verify Model

Calibration and verification of the QUAL2E model requires ambient sampling to determine how well the model simulates conditions in the river. The majority of water quality sampling and flow measurements were conducted in August of 2004 with some supplemental water quality sampling at select locations in August and September of 2005. In addition sediment oxygen demand (SOD) samples were collected at several locations in 2003 and 2004 by EPA. Results of the 2004 and 2005 water quality/ flow monitoring efforts are provided in Appendix 2-A and 3-A respectively. Excerpts from the EPA SOD reports and SOD results are presented in Appendix 4-A. Prior to conducting water quality/flow monitoring, a Quality Assurance Project Plan (QAPP) was prepared by DES and approved by EPA. A copy of the QAPP and complete Data Report are available from the DES, Watershed Management Bureau.

Lists of the measured and observed parameters in general groupings and by station are provided in Tables 2 and 3 respectively. Downstream of the Cheshire Dam, (the focus of the QUAL2E modeling) 16 sites were sampled for various water quality parameters. Flow was measured at 11 locations and continuous reading data loggers were placed at 6 stations along the mainstem. Total Dissolved Solids were calculated based on specific conductivity measurements (see spreadsheets in Appendix 2-A).

Water column sampling conducted in 2004 was primarily used for calibration and verification of the QUAL2E model. In 2004, two rounds of sampling were conducted; one during the week of August 4th and the other during the week of August 11th 2004. SOD sampling conducted by EPA in 2003 and 2004 was also used to calibrate/verify the model.

Each sampling round took one week to complete, required approximately 14 staff members and included water quality sampling, flow sampling, deployment of continuous monitoring equipment (Hydrolabs) and wastewater treatment facility (WWTF) effluent sampling. For each sampling round, the week began by deployment of continuous monitoring equipment (data loggers) at select locations. The continuous monitors were calibrated and set to collect water quality readings every 15 minutes from Monday through Friday. On Tuesday, a composite sampler was set up at the Jeffrey WWTF to collect an effluent sample every hour for 24 hours, and on Wednesday the effluent sample was composited and an instantaneous grab sample of effluent was also collected. On the Wednesday of each sampling round week, 4 water quality sampling teams and two flow teams were deployed on the river. The water quality teams took measurements at selected sampling sites on the mainstem and tributaries in both the morning and afternoon, including collection of water samples to be brought back to the lab for analysis. The flow teams took measurements at 7 main stem river locations and 4 tributary locations.

In general, flows for the August 11th dataset were closer to the 7Q10 low flow in the river, however the August 4th dataset was more complete. This is because on August 11th, the impoundment at Noone Pond was unexpectedly drained while sampling was being conducted. Although drained, and a few data points appear to be outliers, it is still believed that most of the data downstream of the Noone Pond impoundment is reasonably representative of steady state conditions. If anything, the values for dissolved oxygen may be a little high due to slightly higher flows. One would expect that the effects of the release would become less apparent after the impoundments downstream due to available storage.

Table 2: Measured and Observed Parameters

Observations	Hand Held Meter Field Measurements	Data Logger Measurements	Laboratory Analysis
River depth, width,	Air and Water Temperature	Temperature	BOD5 and BOD20
Substrate	Dissolved Oxygen mg/L	Dissolved Oxygen mg/L	Total Suspended Solids
Canopy	Dissolved Oxygen % sat	Dissolved Oxygen % sat	TKN
% periphyton bottom coverage	Specific Conductivity	Specific Conductivity	Ammonia (NH3)
	Flow		Nitrite (NO2)
			Nitrate (NO3)
			Total Phosphorous
			Ortho Phosphorous
			Chlorophyll A
			Sediment Oxygen Demand*****
			CBOD5 and CBOD20 (calculated based on BOD5 and BOD20 and nitrite/nitrate measurements)
			Total Dissolved Solids (calculated based on Specific Conductivity measurements)

* Sediment Oxygen Demand measurements were taken by EPA Region 1 staff in 2003 and 2004.

Table 3: Summary of Measured and Observed Parameters by Station

Station ID	River Mile	Description	BOD-5	BOD-20	CBOD-5 (calculated)	CBOD-20 (calculated)	PHYTO CHLOR "A"	NO2+NO3	NH3	TKN	ORG N (calculated)	TSS	ORTHO P	TP	ORG P (calculated)	Hand Held Meters (Spec. Conductivity (and calculated Total Dissolved Solids), Dissolved Oxygen, Temperature, Spec. Conductivity)	Weather, River Width, Depth, Canopy, % periphyton bottom coverage	SOD*	Flow	Continuous Data Logger (Spec. Conductivity (and calculated Total Dissolved Solids), Dissolved Oxygen, Temperature)
37-CTC	71.14	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
DAM	71.14	Contoocook Lake Dam																		
01-MBR	71.04	Mountain Brook Reservoir		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
DAM	70.07	Contoocook River Dam																		
36-CTC	70.03	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		
DAM	69.76	Timberstone Dam																		
34-CTC	68.2	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
DAM	68.2	Cheshire Pond Dam																		
33-CTC	67.99	Contoocook River																		
32T-CTC	67.78	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
32M-CTC	67.3	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y
NH0100595	67.19	Jaffrey WWTF Effluent	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
32-CTC	66.73	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y
31C-CTC	66.31	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
31B-CTC	65.6	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
00H-TWN	65.55	Town Farm Brook		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
31AT-CTC	65.51	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
02-GRD	65.32	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
31AF-CTC	64.99	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
Withdrawal	64.55	Upland Spring Water																		
01-MDB	64.48	Meadow Brook		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
31-CTC	64.4	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
30M-CTC	63.69	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
30-CTC	63.03	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
DAM	62.95	Noone Mill Dam																		
29-CTC	61.85	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
00H-NUB	61.47	Nubanusit Brook		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	
28-CTC	61.39	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
DAM	61.27	Main St. Dam																		
27W-CTC	61.2	Contoocook River																	Y	
27M-CTC	60.69	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			
27-CTC	59.49	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
DAM	59.49	North Village Dam																		
25Y-CTC	58.7	Contoocook River		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	

Calibration

Calibration is performed in order to maximize the reliability of model predictions. Although the flows were closer to the 7Q10 for the August 11th data set, the August 4, 2004 data set was selected for calibration because it was more complete. A copy of the calibration model input file and output plot files (for various hydraulic parameters, Total Dissolved Solids, UCBOD, nutrients, dissolved oxygen, phytoplankton and periphyton chlor a) are provided in Appendices 5-A and 9-A. respectively.

The model was calibrated in the steady state mode in a step wise fashion in accordance with the following process.

Calibration process description:

Reach Selection: Figure 4 is a schematic showing how the upper Contoocook River was modeled. As shown, the river was divided into 17 reaches based on field investigations and GIS generated profile from 1:24,000 USGS maps. In general, reach boundaries were based on major changes in physical characteristics of the river (ie., impoundments, run-of-river, etc.) . A copy of the profile showing each reach, dam, tributary, point source and sampling station is provided in Appendix 1-A.

Hydraulic Calibration (Flow, time of travel, TDS): Calibrating the hydraulic characteristics of the model is critical to ensuring that the model will accurately predict water quality in the river. Flow input to the model was based on measured flows and calculated incremental flows based on spatial transposition of the measured flow sites (using GIS tools) to all other reach boundaries while accounting for inflows and outflows from point and non-point sources (see Appendix 6-A for flow calculations). Calculated Total Dissolved Solids (TDS) concentrations based on measured Specific Conductivity readings were used to help calibrate the hydraulic portion of the model.

Other studies used to hone the hydraulic calibration included a 1991 Wasteload Allocation Study conducted for the Town of Jaffrey (Ballesteros et.al., 1991). This study extended 2.65 miles downstream from the Jaffrey WWTF (i.e., before the Noone Pond impoundment). Twenty cross sections were taken and the velocities and depths were simulated with the HEC-2 Water Surface Profiles model. The average velocity was approximately 0.55 feet per second at 7Q10 conditions. This agrees well with the calibration run which had higher flows and an average velocity of approximately 0.6 to 0.8 feet per second in this segment.

In addition, a time of travel study conducted in 1977, conducted by the former New Hampshire Water Supply and Pollution Control Commission (NHWSPCC, 1978) was also used as a guide for calibrating the hydraulic portion of the model. This study predicted a time of travel of approximately 0.77 days from the Jaffrey WWTF downstream to the Peterborough WWTF based on a flow of approximately 70 cfs upstream of Nubanusit Brook confluence and approximately 50 cfs below the confluence of Nubanusit Brook. It's not clear from the study exactly where these flows are meant to apply and backup for this 30 year old study is scant; consequently it was used as a guide. More emphasis was placed on selecting velocities that reasonably matched the 2004 flow measurements, the 1991 Ballesteros study (Ballesteros et al., 1991) and first hand knowledge of the river.

Water Quality Parameter Calibration: With the hydraulics calibrated the model was then calibrated for various water quality parameters in the following order:

Temperature was first adjusted to match average observed values in each reach. This was accomplished by turning the temperature mode in the model off and then inputting the average of the morning and afternoon temperatures for the headwater and point loads.

CBODU, nutrients, phytoplankton chlor a and dissolved oxygen were then calibrated. A summary of all of the global and variable rates used in the calibration is provided in Appendix 7-A. The Qual2E User Manual provides set values and recommended ranges for the global and variable rates that are used to calibrate the model. When appropriate, it is acceptable to use a rate value outside the recommended literature range in order to calibrate the model. All rates used to calibrate the Contoocook

River model were within the ranges recommended in the QUAL2E User Manual with the exception of the nitrification rate. The nitrification rate used was 5.0 per day. This value was selected to obtain a reasonable match between measured and predicted values for ammonia and nitrate. Although this value exceeds the recommended maximum value of 1 per day in the QUAL2E User manual (USEPA, 1987) it is within the range of 0 to 9.0 set forth in the "Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition) (*USEPA, 1985*). As explained in this document, nitrifying bacteria can thrive in the beds of shallow streams. Based on this it seems reasonable that at low flows and shallow depths higher nitrification rates are likely to occur as there is better opportunity for nitrifying bacteria in the sediments to interact with ammonia in the water column.

A spreadsheet developed by S. Lawrence Dingman (*Dingman et. al., 1995*), with modifications to account for the fraction available for photosynthesis, cloud cover and forest canopy, was used to determine the Photosynthetic Active Radiation (PAR). A copy of the spreadsheet is provided in Appendix 8-A.

In most cases water quality input for incremental inflows were quite low. However to match observed values for organic nitrogen in the Noone Pond impoundment (Reach 11), had to be increased above typical values which suggests an unaccounted for source in this area. It is believed that it is groundwater related.

Once the hydraulics, CBODU, nutrients and phytoplankton chlor a were calibrated, predicted daily dissolved oxygen concentrations were then checked against observed values which included grab measurements using hand held meters and continuous (ie, every 15 minutes) data collected from dataloggers. In cases where both hand held and datalogger information existed, the average was generally used as the target for calibration.

Sediment Oxygen Demand (SOD) rates were used last to fine-tune the dissolved oxygen calibration. Measured SOD results are presented in Table 4. A comparison of measured versus SOD rates used in the calibrated model is provided in Table 5. As shown in Table 5, calibration SOD values, in most cases, were in close agreement with the values measured in 2003 and 2004 by EPA. The largest difference occurred at Station 30-CTC (Noone Pond impoundment), where the value used in the calibrated model was approximately twice the mean measured value (0.20 compared to 0.09 gm/ft2-day). To determine if this was a reasonable value, average daily river flows (as measured by the USGS at the Peterborough gage) was plotted versus time to determine if flow patterns were significantly different in 2003 when the majority of SOD measurements were made, than in 2004 when water column sampling was conducted for calibration and verification.

As shown in Figure 5, average daily river flows when SOD samples were collected in 2003 were approximately 6 (122 cfs / 22 cfs) to 25 (249 cfs / 9.7 cfs) times higher than when TMDL water column samples were collected in 2004. Because flows were substantially lower at the time of TMDL sampling in 2004 and remained low approximately 6 weeks prior to sampling, its quite possible that SODs in 2004 were higher than in 2003 due to less flushing and more time for organics to settle to the bottom and exert SOD. Consequently, it is believed that the calibration SODs are reasonable.

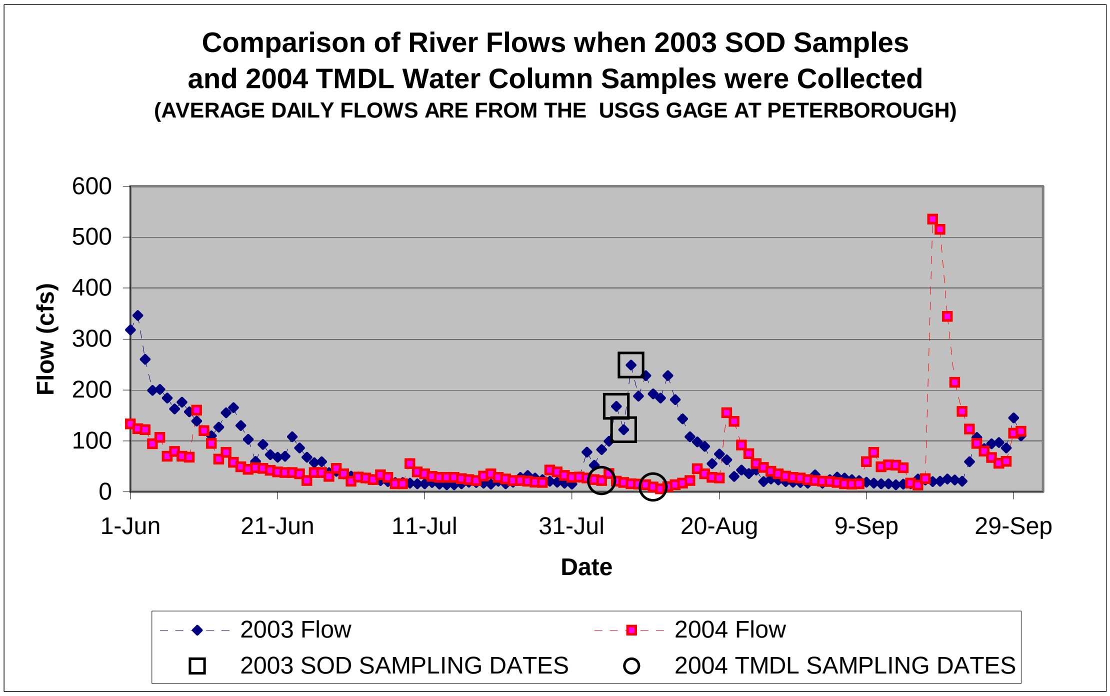
Table 4: 2003 and 2004 Measured SOD Rates

Station	2003		2004		Range within 1 Std. Dev	
	Mean SOD	Std. Deviation	Mean SOD	Std. Deviation	Low	High
	gm/ft^2-day	gm/ft^2-day	gm/ft^2-day	gm/ft^2-day	gm/ft^2-day	gm/ft^2-day
27-CTC	0.104	0.059			0.045	0.164
28-CTC	0.120	0.080			0.040	0.200
30-CTC	0.094	0.039			0.055	0.133
34-CTC	0.480		0.065	0.029	0.036	0.480
36-CTC			0.079	0.022	0.057	0.101
				Min	0.036	0.101
				Max	0.057	0.480
				Mean	0.046	0.216
				Median	0.045	0.164

Table 5: Measured vs. Model SOD Rates

Reach	SOD Station	Mean SOD	Range of SOD within 1 Std. Dev.		SOD used in Calibrated Model
			Low	High	
		gm/ft^2-day	gm/ft^2-day	gm/ft^2-day	gm/ft^2-day
	36-CTC	0.08	0.06	0.10	
	34-CTC	0.48 in 2003 and 0.07 in 2004	0.04	0.48	
1					0.10
2					0.05
3					0.05
4					0.05
5					0.05
6					0.05
7					0.03
8					0.03
9					0.03
10					0.03
11	30-CTC	0.09	0.05	0.13	0.20
12					0.05
13	28-CTC	0.12	0.04	0.20	0.05
14					0.24
15	27-CTC	0.10	0.04	0.16	0.05
16					0.12
17					0.03
	Min	0.07	0.04	0.10	0.03
	Max	0.48	0.06	0.48	0.24
	Mean	0.16	0.05	0.22	0.07
	Median	0.10	0.04	0.16	0.05

Figure 5: SOD vs. River Flow and Year



Method for Determining Minimum Dissolved Oxygen: Since the model was not used in the diurnal mode, it only predicts average daily dissolved oxygen values. To determine minimum dissolved oxygen values, a spreadsheet was developed based on the following formula developed by DiToro (1975) to compute the theoretical diurnal change in DO due to algae.

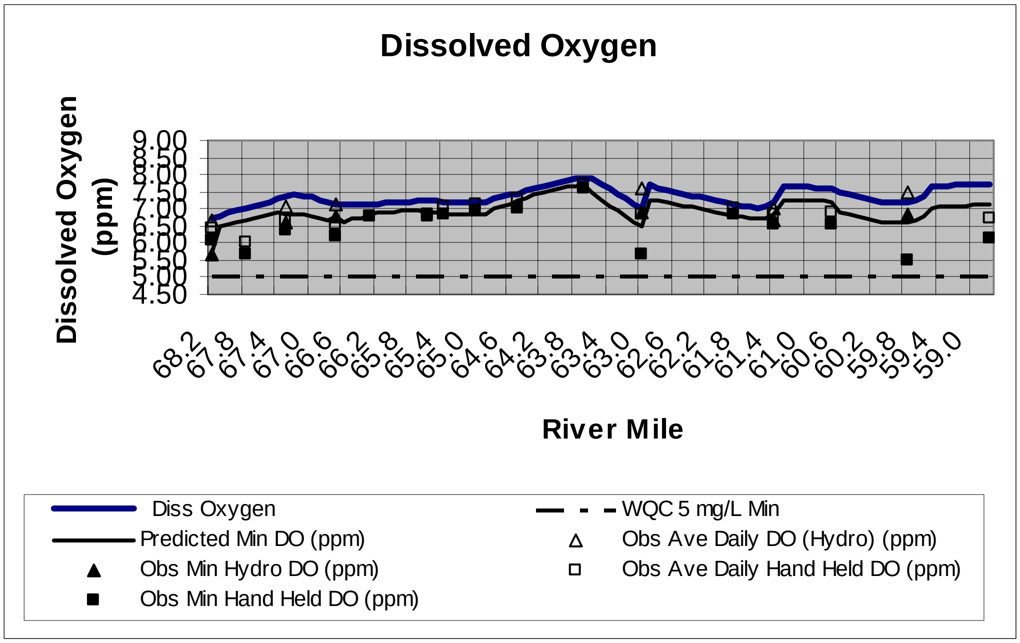
$$Cmax - Cmin = \frac{Pave * [1-\exp(-Ka * f * T)] * [1-\exp(-Ka * T * (1-f))]}{f * Ka * [1-\exp(-Ka * T)]}$$

where, Cmax is maximum daily DO concentration in mg/L
Cmin is the minimum daily DO concentration in mg/L
Ka is reaeration rate (1/day)
f is the fraction of day light is available for photosynthesis (ie, the photoperiod)
T = diurnal period = 1.0 day

Additional information regarding this method and a copy of the spreadsheet is provided in Appendix 10-A.

Plots of the final calibration are provided in Appendix 9-A. A larger plot of the observed versus predicted dissolved oxygen for the calibration run is shown in Figure 6.

Figure 6: Calibration Dissolved Oxygen Plot



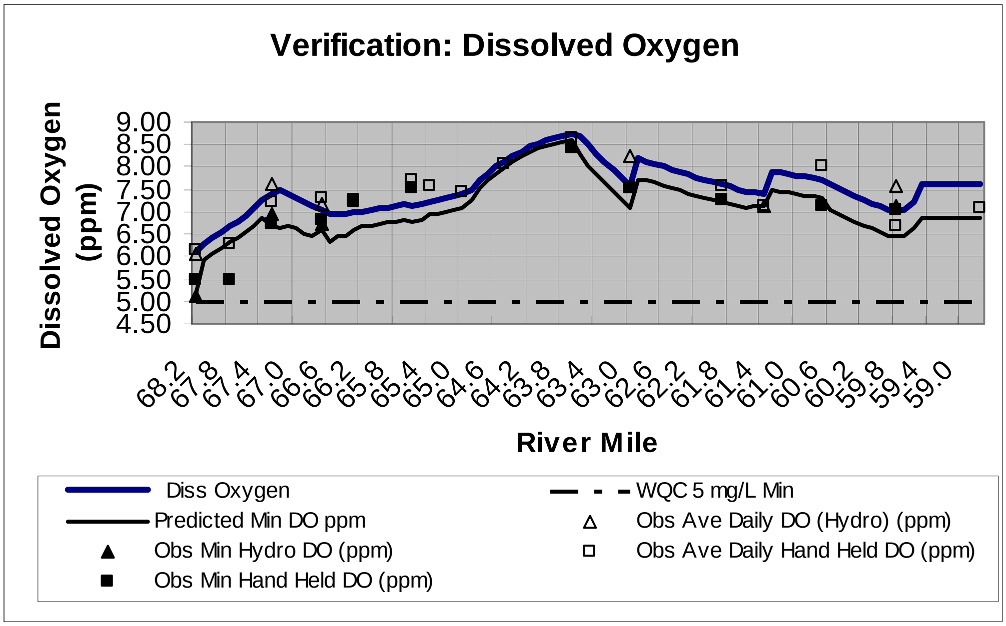
Verification

Once it is believed the model is calibrated, another data set is input to see how well it simulates the river under other conditions. This is called the verification run. If the predicted values in the verification run reasonably match observed values, the model is said to be calibrated and can be used to predict water quality in the river under other loading scenarios.

The August 11th dataset was used for verification. As previously mentioned, this dataset had lower flows which were closer to the 7Q10 low flow than the August 4th dataset, but was somewhat incomplete due the fact that the Noone Pond dam impoundment (Reach 11) was unexpectedly drained while sampling was being conducted. Consequently, when compared to the calibration dataset, some, but not all, of the measured values immediately downstream of the impoundment (reach 13) are representative of when the impoundment was in place. The impact of the drained impoundment on the measured values instream diminishes significantly downstream of reach 13 due to dilution by Nubanusit Brook and the presence of impoundments and their storage capacity.

Data for the August 11th 2004 sampling run may be found in Appendix 2-A. The input file and plots of the output for the verification run are presented in Appendices 11-A and 12-A respectively. A larger plot of the observed versus predicted dissolved oxygen for the verification run is shown in Figure 7. As shown, predicted values for the verification run reasonably match observed values, especially in the reaches upstream of the Noone Pond dam impoundment (Reach 11) and also with observed data downstream of the dam that are representative of when the impoundment was in place. Consequently, it is concluded that the model is calibrated.

Figure 7: Verification Dissolved Oxygen Plot



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Appendices

Appendix 1-A: RIVER PROFILE

Appendix 2-A: 2004 SAMPLING RESULTS

Appendix 3-A: 2005 SAMPLING RESULTS

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